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A REVIEW OF TUNNEL FIRE RESEARCH FROM EDINBURGH

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ABSTRACT

The University of Edinburgh and its alumni have made significant contributions to knowledge in the field of tunnel fire safety engineering. This paper summarises the situation of tunnel fire safety in the early 1970s, when the department of fire engineering was founded and briefly discusses all the contributions to knowledge in the field, made by Edinburgh and its alumni in the past four decades. Research carried out at Edinburgh has changed the way the tunnel safety industry estimates heat release rates in tunnels, has influenced way design fires are specified and has challenged industry opinion about the use of water sprays in tunnels. This paper is part of a celebration of four decades of fire research at Edinburgh.

Keywords

tunnel fires, ventilation, heat release rate, fire spread

INTRODUCTION

The fire research group at the University of Edinburgh was established in 1974 and became the UK's first academic centre dedicated to the study of fire. Over the past four decades, the group has grown to become an internationally recognised authority on fire dynamics and fire safety engineering. One of the many areas of study, within the broader field of fire safety, to which the University of Edinburgh has contributed is the subject of fire safety in tunnels. This paper is a review of the work published by Edinburgh, or by Edinburgh alumni, in the field of tunnel fire safety research with the aim of demonstrating how the University of Edinburgh has influenced and transformed this specific field of research. Because of this intent the paper it is clear that this cannot be a comprehensive review of the subject, indeed it will be a selective and somewhat biased review of this field of study. However, given that this paper was written as part of a celebration of forty years of fire research at Edinburgh, the hope is that the reader will forgive us for this indulgence.

TUNNEL FIRE SAFETY IN THE EARLY 1970s

Before the fire research group was established at the University of Edinburgh, the problem of fire safety in tunnels was generally addressed by using ventilation to move smoke in the event of a fire. Ventilation systems are the original safety system for transport tunnels and for most of the 20th Century were the only fire safety system in most tunnels. The first ventilation system installed in a railway tunnel was in the Edge Hill tunnel, Liverpool, UK, in 1870 (although mechanical ventilation had been commonplace in mine tunnel networks for at least three centuries before this [1]). This was an exhaust fan for the removal of smoke from steam engines. In 1927, the Holland Tunnel in the USA became the first road tunnel equipped with a (fully) transverse ventilation system, that is, a system of ducts and openings provided fresh air into the tunnel at periodic locations along its length, while a second system of openings and ducts extracted polluted air from the tunnel at periodic locations. While these systems were originally conceived as means of replacing polluted air with fresh air, these systems began to be understood as a means of controlling smoke in the event of a fire in a tunnel.

The primary fire safety question for designers of transverse ventilation systems in the 1970s was therefore “how much smoke does the system need to extract?” As smoke production is broadly proportional to heat release rate, this question appeared to be answered to the satisfaction of the industry by a paper presented at the 2nd conference on Aerodynamics and Ventilation of Vehicle Tunnels, held in Cambridge in 1976. A.J.M. Heselden’s paper “Studies of Fire and Smoke Behaviour Relevant to Tunnels” [2] presented, among other things, some data from large pool fire experiments carried out in tunnels. One of the pool fires was estimated to have a heat release rate (HRR) of about 20MW. Unfortunately, Heselden commented that this was equivalent to a HGV fire and the industry now had its answer; a HGV fire in a tunnel was considered to be 20MW from that moment on, and for over two decades after this, the ‘design fire’ used to define the capacity of smoke management systems in tunnels was a 20MW HGV fire [3].

The early 70s was not without innovation in the field of tunnel fire safety; 1971 saw the first tunnel to be equipped with longitudinal ventilation using jet fans, the Bargagli-Ferriere tunnel in Italy. This type of tunnel ventilation system has come to dominate the industry in the four decades since then, and has brought with it some fire safety problems of its own, as we shall see.

In the 21st Century, ventilation systems are only one of several safety systems used in the event of a tunnel fire. Passive structural protection and water spray technologies are increasingly being used to mitigate the effects of fires in tunnels. But in the early 1970s, such systems were rather rare. Indeed, at this time only Japan used sprinklers for fire protection in a small number of its tunnels. We will consider these topics in more detail below.

FOUR DECADES OF TUNNEL FIRES

Since the early 1970s there have been numerous minor and several major fire incidents in underground transportation systems. As engineering in general, and safety engineering in particular, is driven primarily through learning from failure, it is appropriate to chart the incidents which have occurred in the past four decades, as well as to consider the changes in engineering practice and advances in knowledge which have resulted from these. This is an abbreviated list. A comprehensive list of incidents, including further details of the majority of incidents mentioned here, can be found in the literature [4].

The most common kind of tunnel fire in the 1970s appears to have been fires in mass transit/metro systems. The fatal incidents involving fires in New York City (1970), Montreal (1971), Paris (1973), Mexico City (1975), London (1975) and San Francisco (1979) showed the terrible consequences of fires in underground railway systems. Following these incidents, the majority of which involved train collisions as initiating events, a number of measures were imposed on metro systems which reduced the likelihood of collisions in such systems and have thus largely prevented this kind of event in more recent decades.

Of the other tunnel fire incidents in the 1970s, the fire in the Nihonzaka tunnel (1979) had the greatest influence over tunnel fire safety practice. The accident which involved four trucks and two passenger cars led to a fire which ultimately killed seven people and spread to involve 189 vehicles [5]. However, it was the failure of the installed sprinkler system to contain the fire (the water tanks ran dry before the fire was under control) which influenced practice. Primarily on the basis of this incident, the tunnel safety industry took a stance

against the installation of sprinklers in road tunnels, which would not be overturned until after the turn of the century.

The fire involving a fuel tanker in the Caldecott Tunnel, USA (1982), which resulted in seven fatalities, but was successfully extinguished in under two hours, was probably instrumental in changing the industry's perception of hazardous goods transport in tunnels. However, the fire in the Summit Tunnel, UK (1984), which also involved liquid fuel tankers, proved much harder to extinguish, burned for over a day, and resulted in the tunnel closure for several months.

By far the most influential tunnel fire incident of the 1980s, in the UK at least, was the fire in King's Cross Underground station in London (1987) [6]. As is now well documented, this fire exhibited the fire dynamics 'trench effect' which led to very rapid fire growth and brought about flashover in the station's ticket hall in only a few moments, resulting in 31 fatalities and many other injuries. It was the investigation of this incident that first involved researchers from the University of Edinburgh in research into tunnel fire phenomena. Research carried out at Edinburgh, led by Dr Dougal Drysdale, was among the first work to demonstrate and experimentally study the trench effect [7] as well as study it numerically [8].

The largest loss of life in any tunnel fire incident occurred in the metro system in Baku, Azerbaijan in 1995 [9]. Over 200 people died due to the fire and smoke inhalation, largely as a consequence of poor egress provision and the decision to change the direction of ventilation during the evacuation process. A consequence of this incident, is the industry consensus that an emergency ventilation strategy should be established early during an incident, and that the ventilation should not be changed until evacuation is complete. We will consider this strategy in more detail, below.

The first fire in the Channel Tunnel between UK and France occurred in 1996. This has been followed by other significant fire incidents in the tunnel in 2006, 2008, 2011, 2012 and 2015, of which the 2008 fire was the largest in terms of vehicles destroyed and damage caused to the tunnel structure. Nobody has died as a consequence of any of these six incidents. Analysis of the first three of these incidents has been carried out at Edinburgh, as will be discussed below. We have also recently participated in the investigation of the 2015 fire, but these findings have not been published yet.

The spate of road tunnel fires which occurred at the turn of the century in Europe has been well documented in the literature. The fires in the Mont Blanc Tunnel (1999), Tauern Tunnel (1999), St Gotthard Tunnel (2001) and the Fréjus Tunnel (2005) together resulted in sixty fatalities, over a hundred vehicles destroyed, and several years of tunnel closures. These incidents forced the road tunnel safety authorities to reconsider their safety policies and led to a massive investment in tunnel fire research and development, at both national and international scales. As a consequence of these incidents, questions of fire suppression and means of escape provision in tunnels have been raised, and there has been a shift in opinions on these topics in the industry.

The 2007 Burnley Tunnel fire further changed international opinion on the subject of fire suppression in tunnel fires, when the application of a water spray system appears to have effectively controlled a potentially large fire involving two HGV and a car. Other notable fire incidents in the 2000s were the Kitzsteinhorn funicular railway fire (2000) which resulted in 155 fatalities and the arson attack in the Daegu metro (2003) which led to nearly 200

fatalities. So far in the 2010s, there have been few fatal fire incidents, although one fire involving two methanol fuel tankers in a Chinese tunnel led to 31 fatalities in March 2014.

FIRE SPREAD IN TUNNELS

In the early 1990s Dr Alan Beard, then a research associate at the University of Edinburgh, began research into the question of fire spread between vehicles in the tunnel environment. The work was initially based on earlier research into flashover in buildings [10], but grew to include questions of the influence of flame impingement and longitudinal ventilation on whether or not fire would spread. This research led to the FIRE-SPRINT model [11,12,13,14]. This work remains the only model able to describe the conditions under which fire can spread between vehicles which are 100s of metres apart, such as occurred in the Mont Blanc Tunnel fire incident.

FIRE SIZE IN TUNNELS

As noted above, the industry consensus from the 1970s onward was that a HGV fire in a tunnel would be about 20 MW. This illusion was shattered when the EUREKA EU 499 project was carried out in the early 1990s [15]. The only fire test to date of a HGV tractor and trailer with a full cargo of furniture was carried out in a mine tunnel in the north of Norway on 12th November 1992. One of the crucial questions regarding this fire test concerned what the heat release rate of the fire actually was. Various methods of estimating the HRR on the basis of the recorded data (flow velocity measurements, gas concentrations, temperature, etc.) were attempted by teams of researchers from Norway, Germany and the University of Edinburgh. The estimates of HRR varied considerably between the various teams of researchers, see Figure 1, but it is the HRR calculated by Dr George Grant and Dr Dougal Drysdale [16] which has been adopted as the most realistic, and the method used by Edinburgh has now effectively become the industry standard for estimating heat release rate in tunnel fires.

Thus University of Edinburgh research was instrumental in changing the perception of a fire in a tunnel from being 20MW up to about 120MW.

In the late 1990s, Beard continued his research into tunnel fire dynamics by recruiting the author and turning their attention to the question of fire size. The study considered the influence of longitudinal ventilation on fire size in a probabilistic manner, and concluded that fires could grow to be much larger than 120MW, depending on the ventilation conditions. They identified a general trend towards larger fires with increasing longitudinal ventilation velocity [17]. Rather than fixating on absolute HRR estimates, the probabilistic study quantified the effect of velocity by means of a multiplier, relative to the expected HRR of a similar vehicle in an unventilated tunnel. While this methodology has been questioned and criticised by some [18,19], the predicted trends in behaviour have been partially confirmed and validated by subsequent studies and fire experiments [20,21].

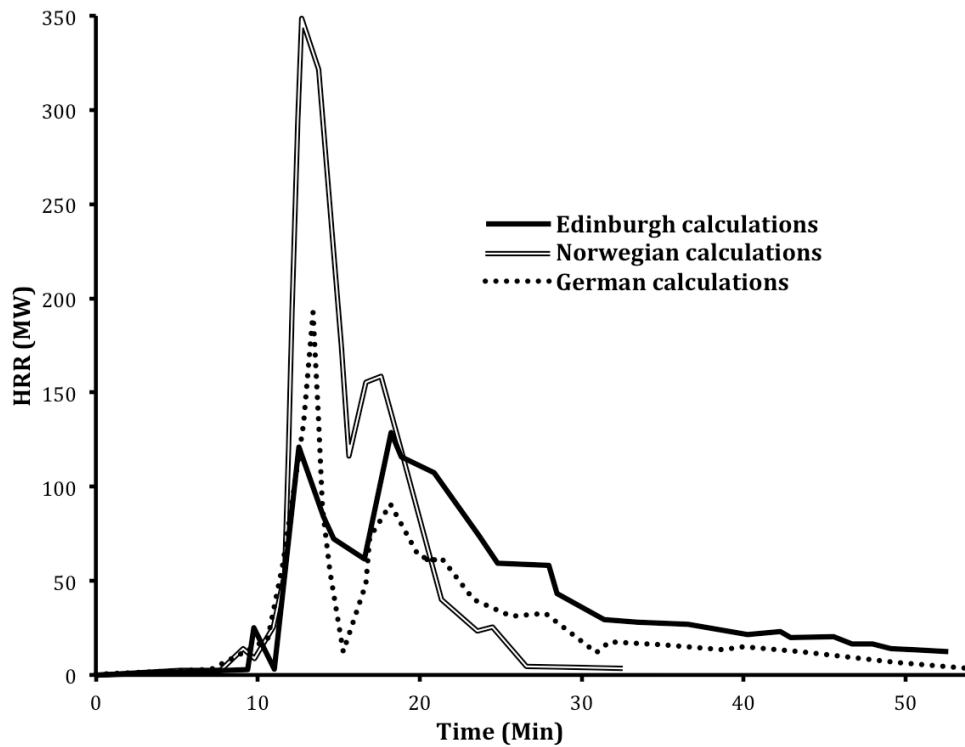


Figure 1 Estimates of the heat release rate of the EUREKA EU 499 HGV fire test, adapted from [15]

CRITICAL VENTILATION VELOCITY

Critical ventilation velocity (CVV) remains the most studied phenomenon in the tunnel fire literature [22]. The fundamental concept of smoke management in longitudinally ventilated tunnels is that, for a given size of fire, there exists a ‘critical’ ventilation velocity sufficient to blow all the smoke produced by a fire to one side of the fire location only. If the ventilation flow is below this level, a layer of smoke may extend away from the fire location in the upstream direction, this is commonly referred to as “backlayering”. Earlier attempts to quantify the variation of CVV with fire size had entered industry practice in the 1980s largely through the model devised by Danziger and Kennedy [23] which was incorporated into the Subway Environmental Simulator (SES) model [24]. This model was based on only a small number of experimental data.

Edinburgh alumni Dr Graham Atkinson and Dr Yajue Wu studied CVV in detail in the late 1990s. Atkinson’s research with Yasushi Oka led to their 1995 paper [25] which is probably the most influential paper in the literature and was the first to adequately define the ‘super critical’ ventilation velocity (SCVV) concept. In their experiments, Oka and Atkinson observed that there is a relationship between fire size and critical ventilation velocity up to a certain limit, but that beyond this limit no increase in ventilation would be required to control the smoke from fires with larger heat release rates (HRR). This can be seen clearly in Figure 2.

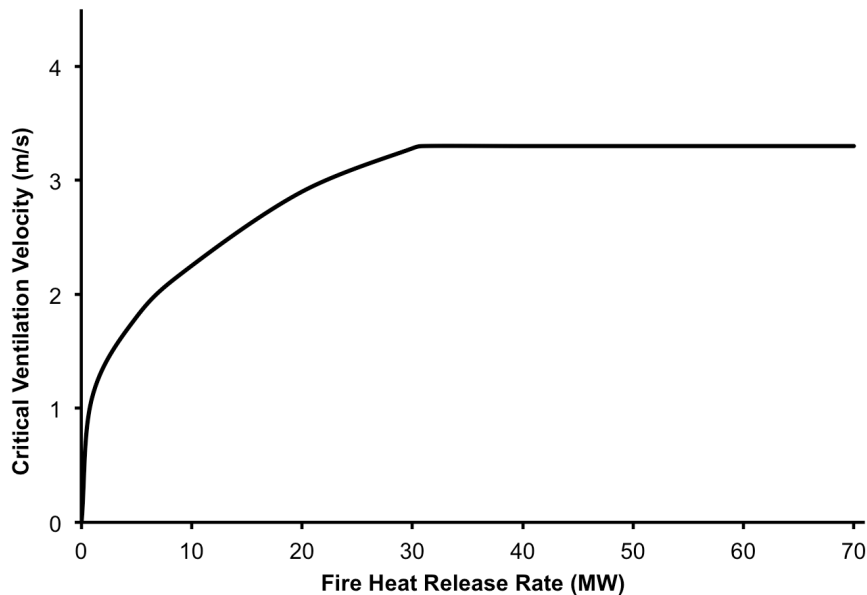


Figure 2 An example of the variation of CVV with HRR, based on Oka and Atkinson [25]

For many typical road tunnels, the SCVV is found to be about 3 ms^{-1} , so many emergency ventilation strategies for longitudinally ventilated tunnels aim to achieve a longitudinal flow of about 3 ms^{-1} in the event of any fire, in order to control smoke. Ventilation studies since 1995 have tended to build on the work of Oka and Atkinson, adding various complexities relating to features such as tunnel slope, considered by Atkinson & Wu [26], aspect ratio, investigated by Wu and others [27,28], and the presence of blockages, investigated in part by Edinburgh alumnus Dr Mark Tsai [29]. The SCVV concept has become widely accepted in the industry.

However, when the industry reworded its requirements for smoke control in terms of critical ventilation velocity, it may have inadvertently overlooked an important fire dynamics phenomenon, the ‘throttling effect’, which we will consider below.

DESIGN FIRES

As noted above, the ‘design fire’ for smoke control in tunnels was for many years considered to be 20 MW. The experience of the EUREKA HGV fire test elevated this estimate, in some cases, to about 120 MW. But the difference between a 20 MW fire and a 120 MW fire was generally taken to be a function of the nature of the fuel present. Carvel & Beard’s research, mentioned above, cast the question in a new light as it highlighted the effect that ventilation has on fire growth and peak fire size.

In past decades the ventilation designer would select a design fire, calculate the critical ventilation velocity required for smoke control and specify the number of ventilation devices required to achieve this flow. Recent work has shown the flaw in this reasoning; increasing tunnel ventilation up to critical ventilation flow may have the effect of enhancing the fire and causing it to burn with a higher heat release rate. In that case, more ventilation may be required [30].

These days a tunnel ventilation designer has to consider that the capacity and characteristics of the ventilation system will potentially influence the behaviour of any fires in the tunnel, in terms of fire growth rate, peak fire size and propensity to spread, as discussed below.

VENTILATION AND FIRE BEHAVIOUR

We have already seen how ventilation can influence the peak size of a fire in a tunnel. Research at Edinburgh also touched upon the questions of fire growth and fire spread. In 2008, the author first observed that experimental fires in longitudinally ventilated tunnels do not exhibit 't²' fire growth behaviour, as commonly expected in compartment fires [31]. Rather, tunnel fire experiments generally seem to grow following a two step linear growth model; the first stage of which (often referred to as the 'incipient' stage) is characterised by a relatively slow rate of burning, and the second stage is characterised by a very rapid growth, often at a rate above 5 MW per minute. These observations were made on the basis of a study of 12 different full scale fire experiments as discussed in [31]. A graph of the apparent relationship between fire growth rate and longitudinal ventilation velocity is shown in Figure 3. From the presented data it is clear that low ventilation velocities (below 1 ms⁻¹) exhibit comparatively low growth rates, below 5 MW/min, while high ventilation velocities (about 6 ms⁻¹) exhibit higher growth rates, about 10 MW/min. However, the most remarkable observation from this data is that some fires ventilated with rates close to about 3 ms⁻¹, that is, close to the emergency ventilation velocity used in many tunnel fire strategies, exhibit very high growth rates of 20 MW/min and above. This apparent relationship has yet to be rigorously proven, but if this behaviour is found to be valid in general, then it would seem that using typical 'emergency' ventilation could result in the worst case for fire growth.

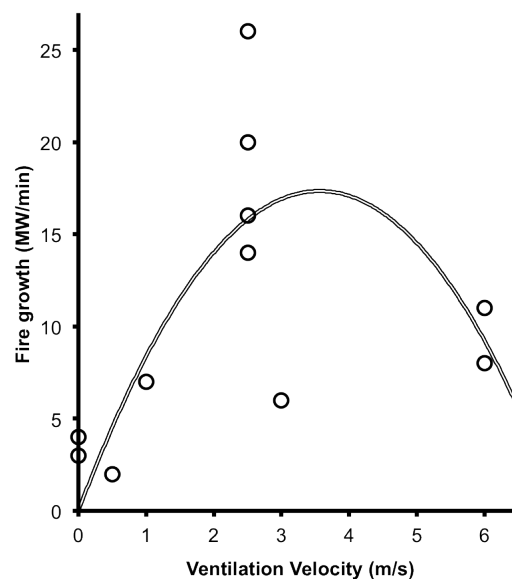


Figure 3 The apparent relationship between ventilation velocity and fire growth, adapted from [31]. The line should not be understood to be anything other than a simple trendline, with a fairly poor 'fit' ($R^2 = 0.5$) due to the scatter of the data.

The author also briefly investigated the influence of longitudinal ventilation on flame tilt and extension, demonstrating (not surprisingly) that increased longitudinal ventilation generally increases the likelihood of flames from a vehicle fire impinging on an adjacent, downstream, vehicle [32].

The University of Edinburgh were invited by the Rail Accident Investigation Branch (RAIB) to assist in their part of the investigation into the 2008 Channel Tunnel Fire. The primary question investigated was the mechanism which caused very rapid fire spread in the incident,

from a localised fire at the time the incident train came to a stop, to a fire involving ten or more carriages about half an hour later. Analysis of the first three Channel Tunnel fire incidents suggested that the main driving force in the rapid fire spread was the reversal in airflow direction, which occurred on two occasions during the 1996 and 2008 fires, but not during the 2006 incident, which in part explains why the fire stayed localised on that occasion [33]. At the time of writing, the University of Edinburgh are again assisting RAIB with their investigations into the 2015 Channel Tunnel fire incident.

VENTILATION AND WATER MIST

Since the spate of catastrophic tunnel fires at the turn of the century, the tunnel safety industry has changed its stance on the use of fixed water-based suppression systems in the tunnel environment. While not explicitly tunnel related, a review published by Dr George Grant et al. in 2000 [34] has become a standard reference demonstrating the benefits of water sprays for fire suppression, both for tunnel applications and in buildings. Grant went on to work with Eurotunnel in their early testing of on-board water mist systems for the HGV shuttle trains [35]. While the tests were generally successful, the suppression systems were never installed in practice, primarily for economic reasons.

However, the University of Edinburgh were among the first to express caution when water mist systems became commonly proposed for use in vehicle tunnels. Work by Dr Guillermo Rein et al. [36,37] suggested that the use of water mist systems in tunnels for fire protection was incompatible with the use of high longitudinal ventilation during the same incidents, as the smallest (and most effective) water mist droplets could be carried tens or hundreds of metres down the tunnel before reaching the road deck, and so would, most likely, miss the target fire altogether. An example of results from Rein's study [36] are shown in Figure 4.

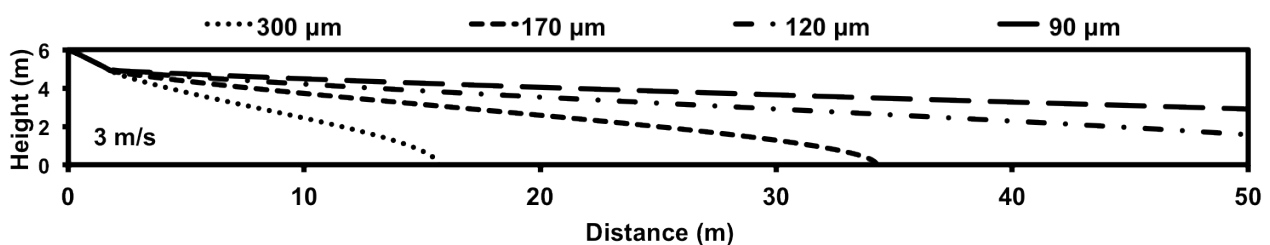


Figure 4 Calculated droplet trajectories for different sizes of water mist droplets, subject to a 3ms^{-1} longitudinal airflow, adapted from [36].

The gauntlet thrown down by this work was taken up during the German funded SOLIT² project [38], which demonstrated the effectiveness of water mist systems in blocking radiant heat, preventing fire spread and protecting the tunnel structure. While it remains true that the lightest droplets may be blown away by the wind, they do appear to provide effective thermal management as they pass [39].

(While the benefits of water mist systems for thermal management, protection of people and protection of structures have been demonstrated through large scale testing, including the SOLIT² project, the current use of terminology such as “Fixed Fire Fighting Systems” and “Fire Suppression Systems” remains controversial, as discussed by the author in a keynote address delivered at the 2012 International Symposium on Tunnel Safety and Security [40].)

VENTILATION AND EGRESS

As discussed above, ventilation influences fire growth, spread and peak size. Ventilation also influences smoke production and behaviour. The inter-relation of these factors is often unclear without detailed study.

A recent work by Michael Winkler (a postgraduate student on the two year “International Master of Science in Fire Safety Engineering” degree programme, taught jointly at the University of Edinburgh, Ghent University in Belgium, and Lund University in Sweden [41]) investigated all the relevant interactions between ventilation, fire growth, peak fire size, smoke production, smoke toxicity, and passenger egress time for the case of fires on passenger trains stopped in tunnels [42,43,44]. Various fire location scenarios were considered, Figure 5 compares the predicted carbon monoxide levels in the smoky egress paths for escaping passengers in the scenario of a fire on the second carriage of the train, and passengers in the scenario of a fire at the mid-point of the train, for both naturally ventilated and mechanically ventilated strategies (the egress path begins at the door on carriage 1 and extends away from the fire towards a cross-passage in all cases). These data, and others went into calculations of fractional effective dose (FED), which suggest that the majority of passengers escaping through the smoke would become incapacitated if forced ventilation was used, while it appears unlikely that any would become incapacitated, escaping in either direction, if natural ventilation was adopted.

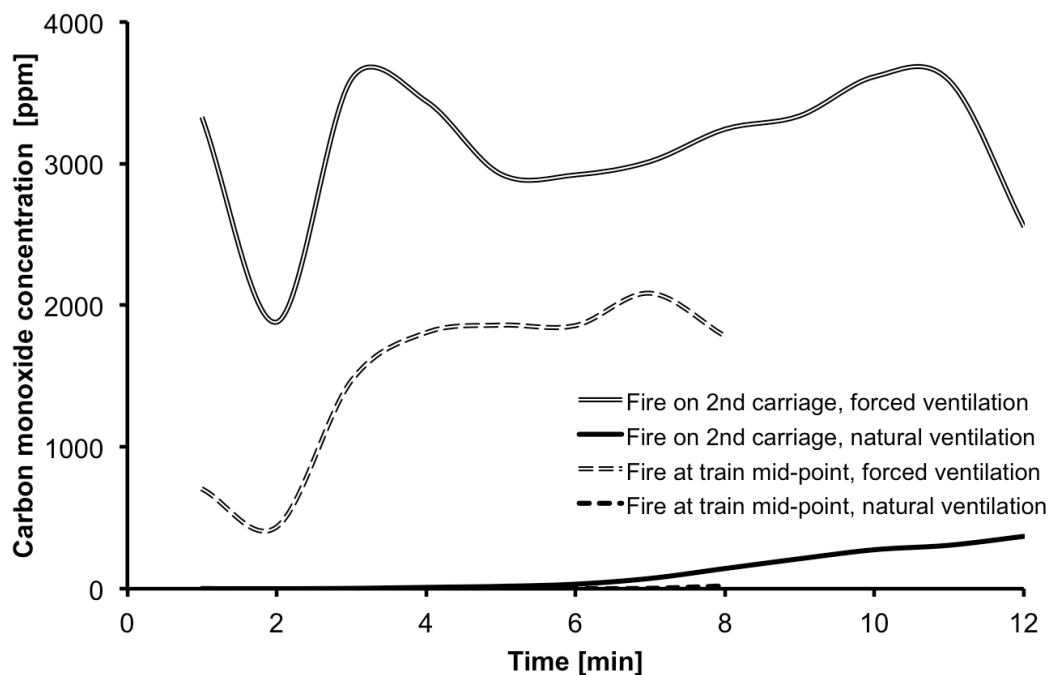


Figure 5 CO concentrations experienced in the tunnel by the first passenger escaping from the train, for each of the scenarios considered, adapted from [42]. Note, the egress paths are different lengths in the two scenarios considered, which is why the dashed lines end after 8 minutes, but the solid lines extend to 12 minutes.

THE THROTTLING EFFECT

A collaboration between the University of Edinburgh and Politecnico di Torino, Italy, saw ground-breaking work in ‘multi-scale’ modelling of tunnel fires being carried out by Dr Francesco Colella et al. [45,46,47]. This work enabled the ventilation performance of full

tunnel networks to be analysed in detail in a computationally efficient manner for the first time. As well as providing a framework for tunnel ventilation analysis for industry, one by-product of the study was the ‘rediscovery’ of the “throttling effect”, an interaction between tunnel fires and ventilation flows which appears to have been reasonably well known in the 1960s and 70s, but vanished from the tunnel fire safety literature after that as the focus of interest moved towards critical ventilation velocity, as discussed above.

In essence, the throttling effect is the tendency of a fire in a tunnel to resist longitudinal airflow; the larger the fire, the greater the resistance. Thus, while critical ventilation studies have shown that no increase in longitudinal flow velocity is required to control smoke from fires larger than the ‘super critical’ limit, in practice, an increasing number of ventilation devices are required to achieve this flow, and hence control the smoke from a fire, as the fire size grows.

A recent study by Edinburgh undergraduate Arnas Vaitkevicius, together with Colella and Carvel, examined numerically the throttling effect phenomenon [48,49]. The effect was clearly demonstrated in their results, as shown in Figure 6.

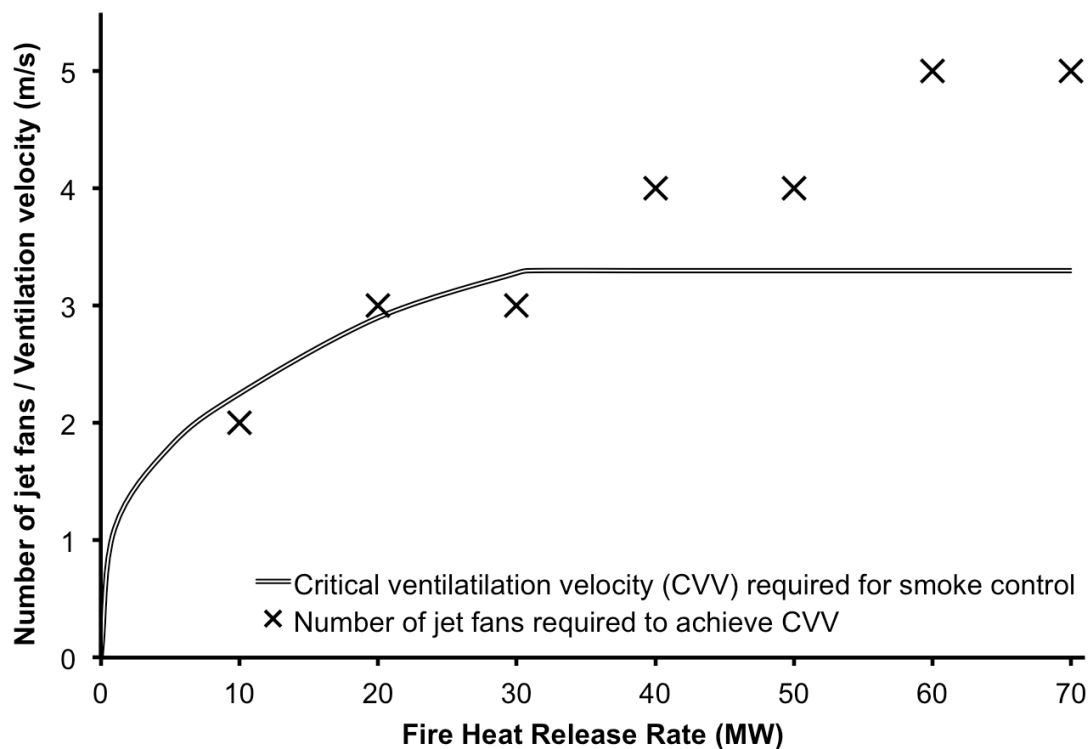


Figure 6 Variation of critical ventilation velocity and the number of jet fans required to generate it with increasing fire size, adapted from [48].

The above has been presented to give a flavour of some of the contributions of the ‘fire group’ at the University of Edinburgh to advances in tunnel fire safety. Other relevant works not described above have also ranged from experimental flammability studies of asphalt roadways [50] to pioneering use of CFD in tunnel fire studies [51]. At the time of writing, studies into smoke management in tunnels under construction and the behaviour of concrete tunnel structures under fire loading are ongoing, other future tunnel fire safety projects are intended.

CONCLUSION

The University of Edinburgh and its alumni have made significant contributions to knowledge in the field of tunnel fire safety engineering over the past four decades. Edinburgh has led the way in reduced scale experimental studies, analysis of full scale data and use of computational fluid dynamics in tunnel fire studies. As new challenges arise in the field of tunnel fire safety, researchers from the University of Edinburgh will continue to study them, and to advance the state of the art in knowledge about tunnel fire behaviour.

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